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Practical Methods for Reducing the Deflagration-to-Detonation Transition Length for Pulse Detonation Engines

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Abstract

Techniques for reducing the deflagration-to-detonation transition (DDT) length are reviewed in this paper. In contrast to previous results from single-shot detonation tube experiments, the present focus is an assessment of the effectiveness and survivability of various DDT devices in an actual engine operating environment. Specific DDT techniques that were considered include Shchelkin spirals, groves, converging-diverging nozzles and orifice plates

Keywords: Pulse Detonation Engines, Deflagration-to-Detonation Transition

Introduction

The impracticality of direct initiation of detonations for pulse detonation engines (PDE), has led to proposals for a combination of techniques to reduce the DDT length to achieve high frequency and reliable detonations. Although the literature on DDT is extensive [1-11], many of the results are based on single-shot detonation tube experiments. The hostile environment in sustained operation of PDEs poses challenges to the development of a successful DDT technique. Detonations can be directly initiated by using high-energy electric arc ignition; however, severe erosion of the electrodes occurs with sustained operation at high frequency (Fig. 1). A hybrid ignition system using a small pre-detonator, containing an easily detonable primary fuel-oxidizer mixture, can be used to generate a detonation front that has sufficient energy to initiate and sustain detonation in the PDE chamber filled with a less detonable fuel-oxidizer mixture. The complexity in regulating and using two fuel-oxidizer mixtures is significant and this technique may not be suitable for all PDE applications.

An alternate approach is to initiate deflagrations via a low-energy ignition that evolve into detonation wave fronts via various DDT enhancing devices. Numerous investigators have shown that these devices can reduce the DDT distance and time significantly. Several non-conventional DDT-enhancing configurations, such as convergent-divergent (C-D) nozzles with different convergent-divergent angles, parallel grooves and helical grooves, were investigated in [9-10] and benchmarked against the well-established Shchelkin spiral. The effectiveness of these devices was characterized in terms of the detonation pressure profiles and time-of-flight (TOF) velocities. Further, durability for sustained operation in a PDE was assessed.

Fig. 1 Erosion of a high-energy arc ignition plug.

Experimental setup

Detonation tube

The detonation tube used was fabricated from ASME Schedule 80 stainless steel pipe with an inner diameter of 24.3 mm and an outer diameter of 33.4 mm. The tube is made of four detachable sections which have standard high-pressure flanges fully welded to their

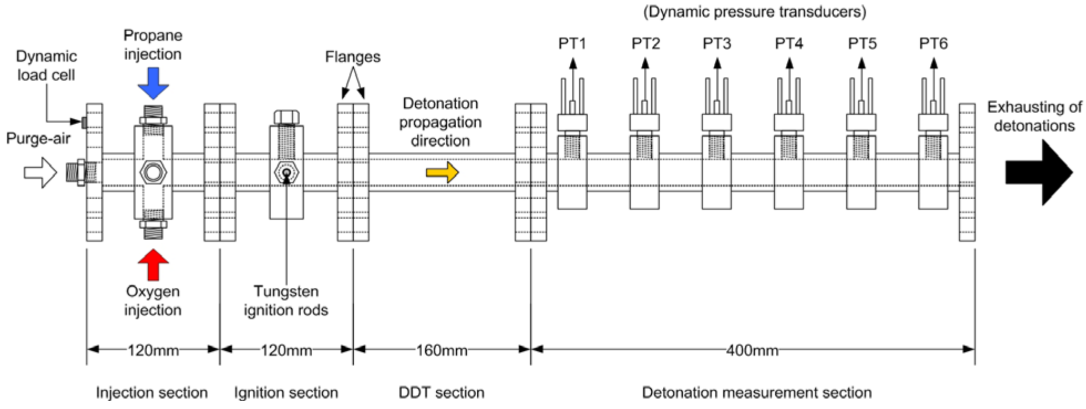


Fig. 2 Schematic of the PDE platform.

ends. These four sections are the injection, ignition, DDT and the detonation measurement section, as shown schematically in Fig. 2[9]. Lanthanated tungsten rods encased in ceramic tubes were used as electrodes for a low-energy igniter. The electrodes were powered by a commercial, off-the-shelf automotive ignition system rated at approximately 150 mJ per ignition spark. The 160 mm long DDT section was used for testing both conventional and non-conventional DDT configurations. Dynamic pressure transducers were located 65 mm apart from each other in the 800 mm long detonation measurement section. When fully assembled, the entire detonation tube measured about 800 mm, giving a length-to-diameter ratio close to 33. The tests were conducted using stoichiometric propane-oxygen mixtures at initial conditions of one atm and 20°C, and the PDE was operated at a firing frequency of 15 Hz. At the prescribed experimental conditions, the detonation cell size λ of stoichiometric propane-oxygen mixture is about 1.3 mm. Further, the generally accepted criterion for the minimum tube diameter for successful detonation propagation is $D/\lambda \approx 13$. In the present experiments, $D/\lambda \approx 18.7$ which exceeds the critical cell size.

Data acquisition and system control

A data acquisition system capable of high-speed simultaneous data acquisition was used for both system control and data acquisition. Signal outputs from the six PCB 111A24 pressure transducers and the PCB 201B05 load cell were acquired at 16-bit resolution. Simultaneous sample-and-hold of the signals was performed at 240 kHz for 5 s during each experiment.

DDT enhancement devices

In addition to the clean-tube configuration, various enhancement devices were tested:

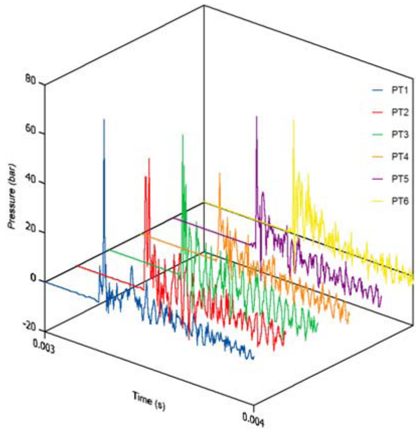
- a helical Shchelkin spiral of 50% blockage ratio, 160 mm in length and 4 mm in diameter (L/D= 6.6) with an 8 mm pitch was made from high-strength stainless steel
- circumferential grooves with zero blockage ratio machined into the stainless steel walls of the detonation tube
- helical grooves with zero blockage ratio machined into the stainless steel walls of the detonation tube
- 15 and 30 deg convergent-divergent nozzle configurations with 50% blockage ratio.

Results and Discussion

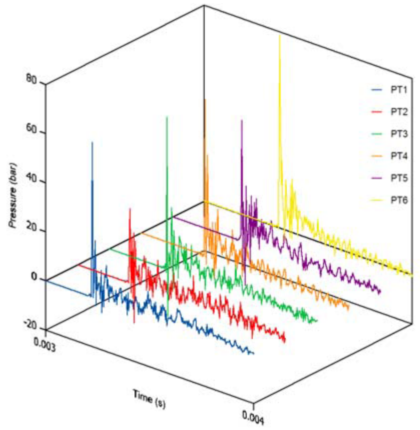
Detonation success-rates

TOF velocities and pressure levels across all six pressure transducers were used to assess the performance of the DDT devices. Performance benchmark was the fraction of successful detonations to the total number of firings. A firing is deemed to lead to a successful detonation only if both the average TOF velocity and peak pressure across the six pressure transducers equaled or exceed the theoretical Chapman-Jouguet (CJ) velocity (2360 m/s) and pressure (36.7 atm) for stoichiometric propane-oxygen detonations. Typical dynamic pressure transducer traces for the clean tube configuration and the Shchelkin spiral are shown in Fig. 3. .Surprisingly, the clean tube configuration without any DDT device registered the highest success rate with 76% of the firings reaching detonation conditions successfully, followed by the Shchelkin spiral configuration with a 70% success rate. The length-to-diameter ratio of the Shchelkin spiral used in the present study was approximately 6.6, which was significantly shorter than the L/D = 12.5 spiral used in an earlier, successful study on DDT enhancements[7]. The shorter spiral length not only failed to enhance the DDT phenomenon but, instead, degraded the detonation success rate to a level slightly lower than was obtained with the clean configuration. Configurations utilizing circumferential and spiral grooves are next with success rates of approximately 61% and 48% respectively. Finally, convergent-divergent nozzle throats achieved significantly lower success rates at 35%, 24% and 17% for the 30 + 15 deg C-D throat combination, the 15 deg C-D and the 30 deg C-D throats respectively. Similar pressure profiles are shown in [9] for the less successful DDT devices. Although high pressures and TOF velocities are achieved in the front of the tube, both die off near the tube exit.

A surprising aspect regarding the above results is that the peak pressure levels shown in Fig. 3 are quite high, typically ranging between 40–60 bar, despite using a relatively modest 150 mJ rated ignition system. This observation is in agreement with the study carried out by Cooper et al.[4] who achieved 40-50 bar peak pressure levels in single-shot DDT-enhanced detonation experiments using only a 50 mJ ignition system. This is further supported by another single-shot experimental detonation study by Li et al.[8], using similar propane-oxygen mixtures which showed peak pressure variation of 40–120 bar, although the ignition energy used by them was more than three times that used here (470 mJ compared to 150 mJ). High peak pressure levels were also observed for some of the less-successful devices, but they were not sustained over the length of the tube, and declined drastically near the tube exit..



(a) Clean-tube



(b) Shchelkin spiral

Fig. 3 Dynamic pressure profiles for successful detonations using clean-tube and Shchelkin spiral configurations.

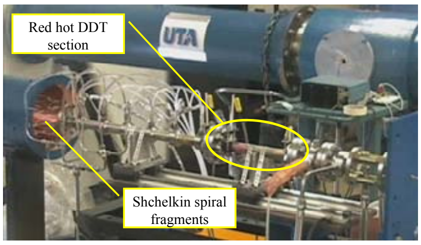


Fig. 4 A PDE without cooling showing red hot DDT section after a few seconds of testing.

Survivability of Detonation-Enhancement Devices

While the Shchelkin spiral is the most common detonation-enhancement device, it is prone to destruction from heating[9]. Fig. 4 shows a red hot DDT section and fragments from a disintegrating Shchelkin spiral being ejected out of the PDE. The destroyed Shchelkin spiral is shown in Fig. 5. Subsequently, the Shchelkin were able to withstand repeated tests at 15 Hz with no deterioration when water cooled [12].

Orifice plates were also shown to be effective in promoting DDT [1]. An advantage of orifice plates is that they can easily accommodate cooling passages, and water-cooled orifice plates also are able to withstand repeated tests at 15 Hz. The CD nozzles also showed no signs of erosion, but were not nearly as effective in enhancing DDT as the Shchelkin spirals or orifice plates.

Conclusions

An experimental investigation of various DDT enhancement devices was conducted at a firing frequency of 15 Hz. TOF velocity results showed that clean-tube configuration was surprisingly able to achieve the highest overall detonation success rate as compared to the use of DDT-enhancement devices. This demonstrates that in the design of compact PDE systems, considerable efforts are required to optimize the DDT device configurations. Despite this, Shchelkin spiral is observed to be the best performer among the DDT enhancement devices, followed by groove configurations and, lastly, C-D throat configurations.

a. A broken piece of the spiral recovered from the PDE tube.

b. The remainder of the spiral that has melted and fused together.

c. Parts of the spiral have been compressed and parts of it has melted away leaving residue.

Fig. 5 Photographs of Shchelkin spirals destroyed in the PDE test shown in Fig. 4.

From the pressure measurements, one possible reason why the groove configurations did not work well is that they were designed with zero blockage-ratio which reduced the production of flame turbulence. The design might have also led to increased trapping of unburned reactants or products which reduce the effectiveness of the grooves to promote flame turbulence. On the other hand, results suggest that convergent-divergent throat configurations have a tendency to destabilize the coupling between the flame and shock fronts.

As for durability, water-cooled Shchelkin spirals, as well as groves and C-D nozzles, were all able to survive sustained operation in the harsh environment. Uncooled Shchelkin spirals, as well as uncooled arc electrodes rapidly deteriorated in sustained operation.

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